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# A MECHANO-ELECTRONIC TRANSDUCER BLOOD PRESSURE RECORDER

BY

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# A Mechano-Electronic Transducer Blood Pressure Recorder.

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**Abstract.**

CLEMEDSON, CARL-JOHAN, CARL-ERIK ENGLUND and HJALMAR PETTERSSON. A mechano-electronic transducer blood pressure recorder. *Acta physiol. scand.* 1959. 47. Suppl. 162. — A manometer has been constructed which can be used for recording blood pressure and other physiological pressure variations. The pressure variations acting on the membrane of the manometer are directly transformed into electric current variations by means of the RCA mechano-electronic transducer tube No. 5734. A high degree of zero stability has been obtained by having the transducer tube working as an oscillator tube. The mechanical construction of the manometer and the mounting of the membrane is described as well as the design of the oscillator and amplifier units. The physical properties of the manometer are discussed, and some step signal response curves obtained with the manometer in connection with cannulas and catheters are presented.

The increasing interest in circulation physiology and especially the rapid development in cardio-vascular surgery have accentuated a widespread need for suitable and reliable manometers and accurate and convenient recording instruments for intra-

vascular pressure determinations. The first instruments employed for blood pressure determinations usually had a mechanical or optical transmission system (*e. g.* FRANK 1903, 1911, 1913, 1925, WIGGERS and BAKER 1924, BROEMSER 1927, HAMILTON, BREWER and BROTMAN 1934, GREGG, ECKSTEIN and FEINBERG 1937, MÜLLER and SHILLINGFORD 1955) but nowadays electrical systems generally are preferred.

The main principles of electrical transmission used are the *photo-electric* (REIN, HAMPEL and HEINEMAN 1940, GILSON 1942, 1943, HELLER and LOCHNER 1952), the *piezo-electric* (LANGEVIN and GOMEZ 1933, BUGNARD, GLEY and NOUGUES 1934, FABRE 1940, MACLEOD and COHN 1941), the *inductive* (HAMPEL 1941, WETTERER 1944, MOTLEY, COURNAND, WERKÖ, DRESDALE, HIMMELSTEIN and RICHARDS 1947, MÜLLER, LASZT and PIRCHER 1948, ELLIS, GAUER and WOOD 1950, 1951, GAUER and GIENAPP 1951), the *capacitance* (SCHÜTZ 1937, LILLY 1942, BUCHTHAL and WARBURG 1943, FROMMER 1943, SKOUBY 1945, MAURICE 1946, LILLY, LEGALLAIS and CHERRY 1947, HANSEN 1947, HANSEN and WARBURG 1947, 1951, TOMPKINS 1949, HANSEN 1950, BAXTER 1953) and the *resistance* principle (GRÜNBAUM 1898, GARTEN 1915, SCHÜTZ 1931, WAGNER 1932). The *strain gage* manometer (BRAUNSTEIN, BROSENE, ABLENDI, GREEN, STRAUSS, HAVENSTEIN and KERSTEN 1947, LAMBERT and WOOD 1947, LAMBERT and JONES 1948, CLEMEDSON and PETTERSSON 1948, MARSH 1949, LAMBERT 1950, JONES and PATERSON 1952) is a special type of resistance manometer.

The development during the last war of the subminiature mechano-electronic transducer tubes originally designed for use in phonograph pickups and microphones (OLSON 1947) and for recording of vibrations in various structures has given the possibility of still another transmission principle for manometers for various biological purposes (AINSWORTH and EVELEIGH 1954). The original physiological use of the mechano-electronic transducer tube was for peripheral pulse contour recording (CURTIS and NICKERSON 1949, CLAMANN 1951, SIMEONE, CRANLEY, GRASS, LINTON and LYNN 1952) but it has also been employed in blood pressure manometers for intravascular application (PETTERSSON and CLEMEDSON 1950, ARNOTT *et coll.* 1950, 1951, CLEMEDSON and PETTERSSON 1951, BÄTTIG and BUCHER 1954, GREEN 1954) as well as for a continuous cuff method (STEGEMANN 1956).

The blood pressure recorder described in this paper is an im-

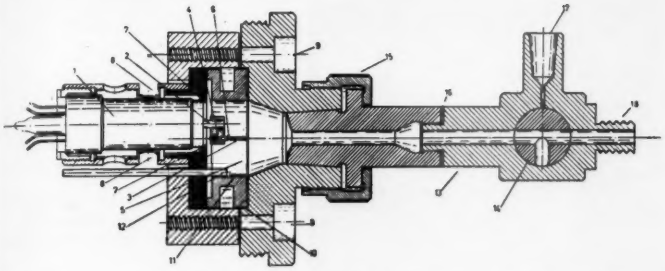

Fig. 1. Cross sectional diagram of manometer. For explanation of figures see text.

proved modification of the one originally described by CLEMEDSON and PETTERSSON (1951) and PETTERSSON and CLEMEDSON (1950, 1956). It is an elastic liquid-containing membrane manometer. The pressure variations acting on its membrane are transmitted and transformed into electric current variations by means of an electronic tube. The RCA mechano-electronic transducer tube 5734 is used. It is a subminiature triode with a movable anode. As the anode current is proportional to the distance between the anode and cathode, any movement of the anode due to the pressure variations will change this distance and cause a change in the internal resistance of the tube and consequently of the anode current. It diminishes with increasing distance and vice versa. The changes in the anode current will cause a variation of the voltage over a resistor in the anode circuit.

## Description of the Manometer.

Fig. 1 shows a cross section of the manometer and the transducer tube (1).[1] The conically shaped anode of the transducer tube is lengthened by means of a small shaft (2) that protrudes at the upper end of the tube through a thin metal diaphragm. The anode is movable in relation to the indirectly heated cathode and the grid. The length of the transducer tube is only about 20 mm and the diameter about 8 mm. It weighs less than 2 g. Its DC anode-supply voltage is max. 300 V and the anode current max. 5 mA. Only very small deflections of the anode shaft are required

[1] In the following, figures within brackets refer to the figures in Fig. 1.

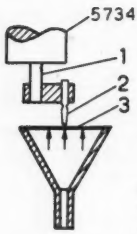


Fig. 2. Schematic diagram of junction between manometer membrane and transducer tube. 5734 is transducer tube, 1 anode shaft, 2 transmission pin, and 3 manometer membrane.

to give considerable variations in the output current. The maximum permissible angular deflection of the anode shaft, which is $\pm$ 0.5 degrees, causes a change in the anode current over the 75 kOhms anode resistor that will give an output voltage of about 40 volts/degree. For further data regarding the tube the reader is referred to a paper by OLSON (1947) and to the RCA Tube Data Book.

To the protruding anode shaft a small pin (3) is attached, fixed to the shaft by means of a small metal junction piece (4). The tube is placed somewhat eccentrically in the tube housing so that the pin rests firmly on the center of the membrane (5) of the manometer (Fig. 1). There is, however, no fixed junction between the pin and the membrane. As the proper connection between the membrane and the anode shaft is of the greatest importance for the function of the manometer some further details concerning it may be given. The pin (3) is 1 mm thick. It has a jag (6) in the center of it giving it a thickness at its weakest point of only 0.1 mm. The end of the pin which is in contact with the membrane, rests in a small shallow indentation in the center of the membrane. This indentation and the jag in the pin are necessary to prevent any possible tendency of the pin to slip when the membrane moves. The contact point must always be exactly the same one in the center of the membrane as even the slightest slipping of the pin would spoil the zero stability (Fig. 2).

The transducer tube is attached to the membrane housing by means of a metal casing. When this casing is properly inserted, the tube is supported only on the annular surfaces indicated with (7) in Fig. 1. The tube must always be completely stationary in relation to the membrane (5). To ensure this, in spite of the fact that the tube and the manometer housing have different co-

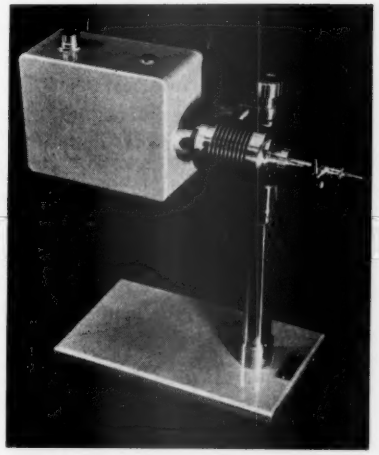

Fig. 3. General view of manometer with stand. The box to the left contains batteries and tuning circuit of the oscillator.

efficients of thermal expansion, the tube casing is furnished with an annular resilient narrowing (8) which allows slight lengthening or shortening of the tube housing. In the casing there are also a number of holes for temperature equalization as the tube grows warm, when it is operating. For the same reason the outer housing of the manometer is furnished with some radiator fins (see Fig. 3).

Another most important thing for the proper function of the manometer is that the pin (3) and the membrane (5) have been so adjusted to each other to impart a certain degree of mechanical tension to the anode shaft. This has been accomplished in the following way. The anode shaft due to its mounting in a diaphragm on the tube has, when deflected, a strong tendency to return to its neutral position. In the manometer the tube is adjusted so that the anode shaft diverges 0.3 degrees from the neutral position. This is schematically illustrated in Fig. 4, where the position $a$ is the neutral position of the anode shaft and $b$ is the angular displacement ($\alpha_1$) of the shaft caused by the adjustment of the transmission pin (3) against the membrane of the manometer. The extent of deflection of the anode shaft can be adjusted by means of the screws (9) which are also used for fixing the membrane. The position $b$ is the position of the shaft, when no pressure is applied to the membrane. When the membrane is influenced by an alternating pressure (*e. g.* blood pressure) the anode shaft

Fig. 4. Schematic diagram illustrating the deviation of the anode shaft. *a* is neutral position of the shaft. *b* is position of shaft caused by the adjustment of the transmission pin to the membrane, *i. e.* the position of the shaft when the membrane is in its neutral position. Dashed lines indicate deviations of shaft when pressure is acting on the membrane.

$a_1 \approx + 0.3$ degrees; $a_2 \approx \pm 0.15$ degrees.

deviates as indicated by the dashed lines in Fig. 4. The working angular deflection ($a_2$) of the pin is about $\pm$ 0.15 degrees. Through its tendency to return to the neutral position *i. e.* position *a* in Fig. 4, the anode always presses the end of the pin firmly against the membrane and will follow its movements exactly.

Due to the adjustment of the anode shaft mentioned above, only a small part of the total allowable deflection range of the anode is made use of in the manometer. This is advantageous from the point of view that the working characteristic of the tube is not exactly linear. By employing such a small range this error is essentially avoided and can be corrected to complete linearity by a suitable amplifier.

The membrane (5) is by means of the screws (9) fixed against an elastic metal washer (10). The mounting of the membrane will be further dealt with below. The air-filled space (11) behind the membrane is connected with the outside air by means of a thin cannula (12). This will prevent pressure variations on the membrane and spoiling of the zero stability caused by variations of temperature in the manometer and of the surrounding air.

The tube (13) for the connection of the manometer with a cannula or a cardiac catheter has a three-way stop cock (14) so that the manometer can be set to zero or flushed during an experiment. The lumen of the connection tube is 2 mm and it has been chosen so wide in order to cut down the damping in the manometer so that it will be insignificant compared with that in the catheter or cannula attached to the manometer. These will thus set the limit as far as damping is concerned.

The connecting tube has been made in two pieces. The reason

for this was only to facilitate the construction and mounting of the coupling nut (15) for the attachment of the tube to the membrane housing. Inserted between the two tube pieces is a silver gasket (16). The branch (17) has an inner conical bore for a record syringe nozzle. The branch (18) is threaded to allow the use of various needle nipples (record, Luer etc.).

All parts of the manometer, with the exception of the transducer tube (1), the membrane (5) and the washer (16), are made of stainless steel.

## Mounting of the Membrane.

The manometer membrane is made of platinum. It has a thickness of 0.2 mm and its free diameter is 12 mm.

A proper mounting of the membrane is critical for the functioning of the manometer. In order to obtain a higher natural frequency of the membrane without increasing its thickness and mass, it was considered desirable to impart to the membrane a certain degree of radial tension. The coefficient of thermal expansion of the membrane is different from that of the membrane housing and, therefore, the desired degree of radial tension can be obtained by clamping the membrane in the housing at a temperature that is considerably lower than the normal working temperature of the manometer. We have found it most suitable to mount and clamp the membrane in a freezing box at a temperature of about $-55°$ C. If another predetermined natural frequency is desired another temperature should be chosen. This way of mounting the membrane will also vouch for that the membrane will be completely plane and that it after a deflection always will return exactly to its initial position. Furthermore, the risk of fluctual changes of the natural frequency of the membrane due to temperature variations during operation will be less with this way of mounting the membrane.

## Electronics of the Manometer.

*Oscillator.*

In connection with the work on the designing of a suitable amplifier for the manometer, it was found that a number of advantages could be obtained by having the transducer tube working as an oscillator tube. In this case the transducer tube anode

voltage needed will be only about 65 V and the anode current about 300 $\mu$A. The anode dissipation will then be too small to cause any inappropriate rise in the operating temperature of the manometer. This in turn will improve the zero stability of the manometer and the time to full stability will be greatly reduced. Another advantage is the possibility of using the manometer oscillator directly for radio transmission of the blood pressure to a radio receiver.

As the essentially new feature of the present manometer system is the use of the transducer tube in an oscillator system, the principle of this will be described somewhat more in detail.

For a triode with plane parallel electrodes the relation between the amplication factor ($\mu$) and the geometric properties of the tube can be written in the following simplified form (see Reference Data for Radio Engineers):

$$\mu = \frac{2.7\, a \left(\frac{b}{a} - 1\right)}{d \ln \frac{d}{2\pi\, r_g}} \tag{1}$$

if $a$ is the grid-cathode distance, $b$ the anode-cathode distance, $d$ the grid-wire spacing and $r_g$ the radius of the grid wire.

If $U_2$ is the plate voltage and $U_g$ the grid voltage the anode current ($I_a$) is:

$$I_a = \frac{2.3 \times 10^{-6}}{ab} \left( \frac{U_g + \frac{1}{\mu} U_a}{\frac{1}{\mu} + 1} \right)^{3/2} \tag{2}$$

and the grid-plate transconductance ($S$) is:

$$S = \frac{3.5 \times 10^{-6} \left( U_g + \frac{1}{\mu} U_a \right)^{1/2}}{ab \left( 1 + \frac{1}{\mu} \right)^{3/2}} \tag{3}$$

It is evident from these formulae that the tube characteristics will be changed if the distance between the anode and the cathode

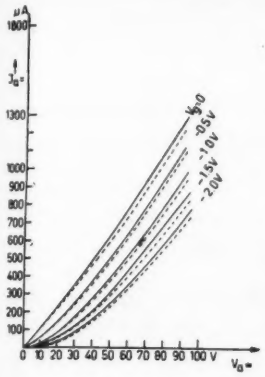


Fig. 5. Anode current of RCA transducer tube 5734, connected for pressure recording, as a function of the anode voltage at different grid bias ($V_g$).

Continuous lines: membrane pressure 0 mm Hg; dashed lines: membrane pressure 300 mm Hg.

In this case the tube has not been connected as an oscillator tube.

is changed in the transducer tube when a pressure is applied to the manometer membrane (Fig. 5).

An analysis of the change of the tube characteristics as a function of the pressure applied to the manometer membrane and transmitted to the anode shaft shows that an increase of the pressure acting on the membrane from 0 to 300 mm Hg, the plate voltage being 65 V and the grid bias being $-0.5$ V, will give an increase of about 5 per cent of the plate current and the grid-anode transconductance and a lowering by 4 to 7 per cent of the dynamic plate resistance ($R_i$) of the transducer tube.

If the transducer tube is connected in an AC amplifier circuit the amplification ($F_0$) obtained at an anode loading $Z_b$ and zero pressure to the membrane will be:

$$F_0 = S \frac{R_i Z_b}{R_i + Z_b} \tag{4}$$

At a pressure load on the membrane of 300 mm Hg the amplification is:

$$F_{300} = (S + \Delta S) \cdot \frac{(R_i - \Delta R_i)\ Z_b}{(R_i - \Delta R_i) + Z_b} \tag{5}$$

If $Z_b \geqslant R_i$ one can omit $R_i$ and $(R_i - \Delta R_i)$, respectively, in the denominators of (4) and (5), obtaining:

$$F_0 \approx SR_i = \mu \tag{6}$$

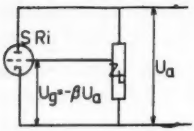


Fig. 6. Schematic diagram of the principle of oscillator. For explanation of symbols see text.

and:

$$F_{300} = (S + \Delta S)\ (R_i - \Delta R_i) \tag{7}$$

Since the percental increase of $S$ has about the same value as the corresponding decrease of $R_i$ the change in amplification is insignificant in this case.

If on the other hand $Z_b \ll R_i$ one obtains:

$$F_0 = SZ_b \tag{8}$$

and:

$$F_{300} = (S + \Delta S)\, Z_b \tag{9}$$

In this case an increase of the amplification and thus of the amplitude is obtained, when the pressure acting on the membrane is increased. The maximum change of amplification ($\Delta F$) is about 5 per cent of $F_0$.

In the foregoing discussion it has been assumed that the control grid of the transducer tube is fed an alternating voltage from an external oscillator. In the present manometer the transducer tube itself is, however, connected as an oscillator. This is accomplished by feedback of the output voltage to the control grid in a phase such that the tube will be self-oscillating. The condition for self-oscillating of an oscillator can be expressed by the relation:

$$-\beta Z_b S = 1 \tag{10}$$

if $\beta$ is the feedback factor. Since $S$ and $Z_b$ are positive quantities, it follows that $\beta$ must be negative which means that a phase constant of 180° must be effected through the feedback. If the impedance $Z_b$ is an oscillatory circuit on the anode side, a lower voltage is inductively tapped from it to the grid. Then $Z_b$ is large whereas $\beta$ is less than 1. If, on the other hand, the oscillatory circuit is connected to the grid side, the impedance $Z_b$ is constituted by a feedback coil in the plate circuit (see Fig. 6). In this case $Z_b$ has a low value whereas $\beta$ is larger than 1.

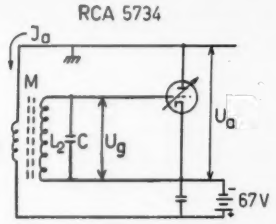


Fig. 7. Circuit diagram of oscillator with the transducer tube RCA 5734 connected as an oscillator tube.
Symbols are explained in text.

Fig. 7 shows a basic diagram of the oscillator with the transducer tube connected as an oscillator tube. The metal case of the tube is connected to the anode and has earth potential but the grid and cathode leads are on a high frequency voltage. The grid coil ($L_2$) and the feedback coil ($L_1$) are wound on the same bobbin furnished with a compressed iron power core. By means of this core the feedback factor ($\beta$) can be varied within wide limits without any effect on the frequency.

The anode loading at resonance ($Z_{b_{res}}$) of the tube can be written:

$$Z_{b_{res}} = \frac{\omega^2_0 M^2}{r} = \left(\frac{M}{L_2}\right)^2 R_0 \tag{11}$$

if, according to Fig. 8, $L_1$ and $L_2$ is the feedback- and the tuning inductance respectively, $\omega_0$ the angular frequency, $M$ the mutual inductance $= k\sqrt{L_1 L_2}$, $r$ the series loss resistance in $L_2$ and $R_0 = \dfrac{L_2}{rC}$ is the parallel impedance of the tuning circuit at resonance.

The diagram of the oscillation characteristic in Fig. 9 shows in a simplified manner the dependence of the self-oscillating condition and the degree of modulation on the feedback factor ($\beta$). Each characteristic curve corresponds to a definite operating point. The angle $\alpha$ gives a measure of the degree of coupling if

$$tg\alpha = \frac{\Delta U_g}{\Delta I_a} \tag{12}$$

and

$$\beta = -\frac{\Delta U_g}{\Delta U_a} \text{ or } \Delta U_g = -\beta \Delta U_a \tag{13}$$

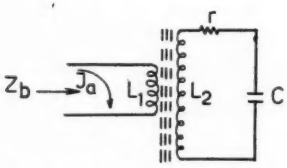


Fig. 8. Equivalent diagram of anode load.

$I_a$ which is the anode alternating current, is assumed to be constant ($R_i \gg Z_b$).

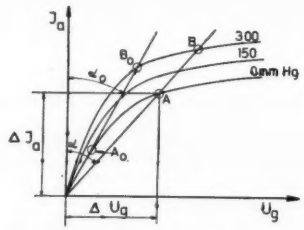


Fig. 9. Diagram of oscillating characteristic showing in a simplified way the dependence of the self-oscillation condition and the degre of modulation on the feedback factor ($\beta$).

For explanation of symbols see text.

If the last expression is inserted into the expression for $tg\alpha$ one obtains

$$tg\alpha = \frac{\Delta U_g}{\Delta I_a} = -\frac{\beta \Delta U_a}{\Delta I_a} = -\beta Z_b \tag{14}$$

According to the definition of the static grid-anode transconductance ($S_0$) one obtains

$$S_0 = \frac{\Delta I_a}{\Delta U_g} = \frac{1}{tg\alpha_0} \tag{15}$$

if $\alpha_0$ is the smallest value of $\alpha$ for which self-oscillation is obtained. The condition of self-oscillation thus is fulfilled when

$$tg\alpha = tg\alpha_0$$

or when

$$-\beta \cdot Z_b = \frac{1}{S_0} = tg\alpha_0 \tag{16}$$

A working curve for $\alpha > \alpha_0$ is in Fig. 9 drawn through origo and through the points $A$ and $B$. When no pressure is applied to the membrane the working point $A$ is obtained. If an increasing pressure is applied there is a displacement towards point $B$ which corresponds to a membrane pressure of 300 mm Hg. It is evident from the diagram that a relatively large coupling factor gives a low degree of modulation and a good linearity. A working curve for the limit of self-oscillation ($\alpha = \alpha_0$) gives the working points

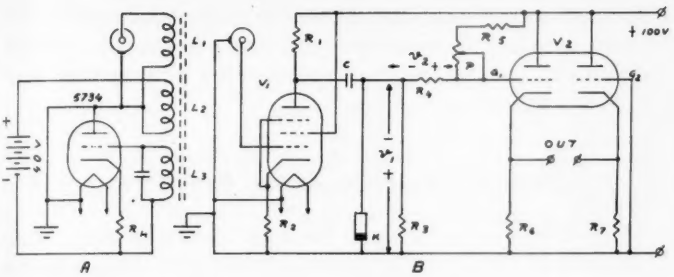


Fig. 10. Wiring diagram of oscillator (A) and amplifier (B).

| | | | | | |
|---|---|---|---|---|---|
| $R_k$ | 1 | $k\ \Omega$ | $R_5$ | 2 | $M\ \Omega$ |
| $R_1$ | 10 | $k\ \Omega$ | $R_6$ | 120 | $\Omega$ |
| $R_2$ | 1 | $k\ \Omega$ | $R_7$ | 120 | $\Omega$ |
| $R_3$ | 0.5 | $M\ \Omega$ | $P$ | 0.1 | $M\ \Omega$ |
| $R_4$ | 0.33 | $M\ \Omega$ | $C$ | 470 | $pF$ |

$A_0$ and $B_0$. In this case there is a high degree of modulation but also a high degree of non-linearity.

*Amplifier.*

The modulated high frequency signal from the oscillator is fed into the coupling coil $L_1$ which is directly connected to an output amplifier (see Fig. 10).

The signal is amplified in the high-frequency amplifier tube $V_1$ and is then demodulated over the crystal diode Philips OA 85. The diode is connected in such a way that a negative direct current voltage level is obtained over the resistance $R_3$. An increased pressure on the membrane of the manometer will cause an increase of the high-frequency amplitude and this will raise the negative direct current voltage level which is of the magnitude of 20 V. In order that it shall not block the grid $G_1$ of the differential amplifier, $V_2$, a voltage divider, $R_4$—$P$—$R_5$, is introduced. Across the resistance $R_4$ a positive voltage, $V_2$, is developed which opposes the rectified signal voltage, $V_1$, which is negative. The voltage $V_2$ is adjusted to make the differential amplifier balanced when the membrane pressure is zero. An increase of the signal voltage $V_1$ will cause a decrease of the potential of the grid $G_1$ and thus the anode current in this part of the triode $V_2$ is lowered resulting in an unbalance of the currents through the cathode resistors $R_6$ and $R_7$.

The differential amplifier $V_2$ has a cathode-follower circuit in order to obtain an appropriate impedance conversion to about 100 ohms for the connection of the amplifier to a recorder with low input impedance.

## Physical Properties of the Manometer.

The usable pressure range of the manometer is from — 60 to + 300 mm of mercury. The volume capacity of its hydrodynamic system when no needle or catheter is attached, is about 1.2 $cm^3$. The sensitivity of the transducer system is so high that a deflection of the center of the membrane of only $10^{-5}$ mm will be recorded. The total volume displacement when the pressure changes from 0 to 300 mm Hg, is less than $10^{-5}$ $cm^3$.

The goal for the improvement of our original manometer (CLEMEDSON and PETTERSSON 1951) has been among other things to comply with the following requirements: high stability, insensitivity to movement, linear calibration, usability with long leads, insensitivity to temperature, humidity and acceleration, simplicity of operation and of sterilization and removal of air bubbles in the hydrodynamic system, imperviousness to electrolyte solutions, and last but not least, since we use the manometer in connection with high explosive blast research, sturdiness in construction. Most of these requirements have been listed by WOOD (1956) who emphasizes them to be equally or more important than the dynamic characteristics of the manometer system.

The problems of natural frequency and damping of elastic manometers have been dealt with in detail by FRANK (1903) and especially by HANSEN (1949, 1950), HANSEN and WARBURG (1950) and WARBURG (1950) and therefore they will be only cursorily treated.

The degree of damping and the natural frequency of a manometer will be dependent on the total volume elasticity of the manometer system which in turn depends on the physical properties of the membrane, *i. e.* its modulus of elasticity and its diameter, thickness and degree of tension produced by the low temperature clamping. When a needle or catheter is attached to the manometer the length and inner diameter of the needle or catheter will be critical.

The degree of damping ($a$) can be calculated from the following formula:

$$a = \frac{4n}{R^3}\left(\frac{L}{\pi E}\right)^{1/2} \tag{17}$$

where $E$ is the modulus of volume elasticity in dynes · cm$^5$, $L$ the length and $R$ the inner radius of the needle or catheter in cm, and $n$ the viscosity of the liquid in the system expressed in poise. The length of a needle or catheter in cm that will give a desired degree of damping can be calculated from

$$L = \frac{a^2 R^6 \pi E}{16 n^2} \tag{18}$$

The damped natural frequency ($f_1$) in cps is:

$$f_1 = \frac{1}{2\pi}\left[\frac{\pi R^2 E}{L} - \left(\frac{4\eta}{R^2}\right)^2\right]^{1/2} \tag{19}$$

It has been assumed in these formulas that the specific gravity of the liquid in the manometer (saline, blood) is 1. From the practical point of view this will be justified. The formulas apply to membranes without radial tension. If the membrane has been imparted a certain degree of radial tension, the conditions will be more complicated. This case will be treated in more detail elsewhere.

The step signal response and damped natural frequency of the present manometer has been tested without and with a cannula and a catheter, respectively, attached to the connection tube (13, Fig. 1) of the manometer. The following set up was used for the frequency testing. The manometer system, the connection tube and the cannula or catheter was filled with completely air free normal saline solution and was made a closed system by closing the tip of the tube or needle (catheter) by means of a small rubber stopper. The piece of rubber was fixed on the armature of an electromagnet. A plunger device was attached to the closed manometer system so that the pressure could be increased in the system. The pressure could then be suddenly released when the rubber stopper was removed by closure of the electromagnet current.

The cannula used had a length of 51 mm and an inner bore

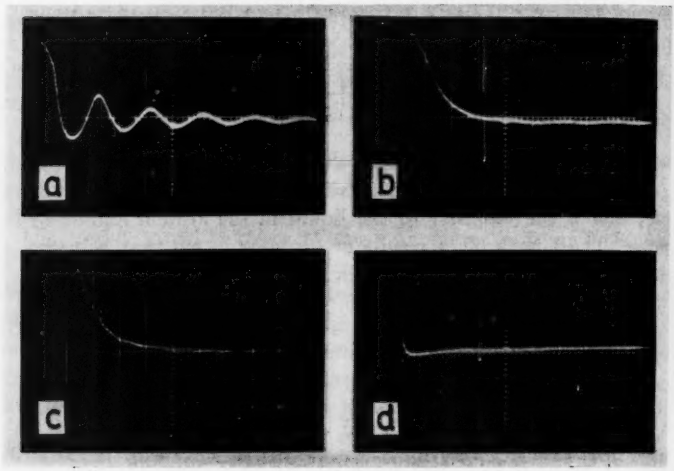


Fig. 11. Step signal response curves of the manometer.

*a* with manometer and connecting tube only;
*b* with a steel cannula attached to the connecting tube. Inner diam. of cannula 0.55 mm, length 51 mm.
*c* and *d* with a catheter. Length of catheter 520 mm and inner diam. 0.70 mm. Time (between vertical lines): *a* and *b* 10 millisec., *c* 20 millisec. and *d* 200 millisec.

of 0.55 mm. The catheter used was an USCI X-ray opaque catheter No. 5, with an inner diam. of 0.70 mm and a length of 520 mm. The test pressure used was 150 mm Hg. The frequency curves were recorded with a cathode ray oscillograph (Fig. 11).

When the electromagnet current was closed and the closed pressure system of the manometer opened, the pressure decreased from 90 to 10 per cent of the initial 150 mm Hg in a certain time interval, $\tau$. This time is a measure of the upper cut-off frequency, $f_u$, which is defined as the frequency at which the response is decreased in the ratio of $\frac{1}{\sqrt{2}}$.

The upper cut-off frequency $f_u$ may for practical purposes be calculated from the following formula (*c. f.* WALKER and WALLMAN, 1948):

$$f_u = \frac{0.35}{\tau} \qquad (20)$$

Fig. 12. Carotid artery pressure curve from a rabbit recorded with the manometer.

For the manometer system with no cannula or catheter attached $\tau \approx 3$ millisec., and the damped natural frequency $\approx 50$ cps. (see Fig. 11 a). With the cannula attached, $f_u$ was about 22 cps. (Fig. 11 b) and with the catheter about 10 cps. (Fig. 11 c and d). The use of a thicker membrane will increase the damped natural frequency.

It is most important to avoid the trapping of air bubbles, in the liquid system when filling a manometer. Generally, the best way of excluding any air or gas from the system is by boiling the manometer in saline or distilled water. The manometer is furnished with a small cap which when screwed over the electrical contact gives a water-proof closure enabling the boiling of the manometer. Owing to the shape of the manometer chamber and to the slightly cone-shaped bore of the tube connecting the manometer chamber with the needle or catheter, this manometer can, however, be conveniently filled with saline from a syringe without air bubbles being trapped in the system.

The manometer has been used for intravascular pressure measurements essentially in animal experiments in connection with blast injury research. Fig. 12 shows a pressure curve from the carotid artery of a rabbit. A shortened cardiac catheter (USCI no. 7, length 20 cm) connected to the manometer was tied in one of the common carotid arteries for the recording. A left ventricle pressure recording is shown in Fig. 13. The curve was obtained by heart puncture with a hypodermic needle (length 70 mm, inner diam. 1.8 mm).

The manometer can also be employed for pressure recordings

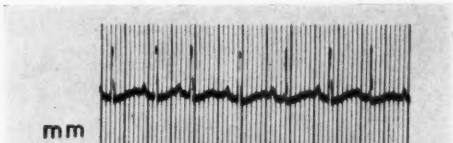


Fig. 13. Left ventricle pressure curve of a rabbit obtained by heart puncture.

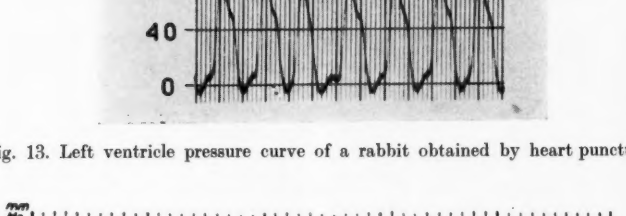


Fig. 14. Pressure recordings from an air filled cyst in the neck of a patient. Curves A—E were recorded during swallowings and curves F and G during straining.

in gas or air filled cavities. In Fig. 14 is shown a number of pressure recordings in an air filled cyst in the neck of a patient during swallowing and straining.

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